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RESULTS OF R&D BILLET WITH SPACED 60/61 SUBELEMENTS MADE BY OST WITH RRP TECHNOLOGY

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Abstract:

In the process that leads a flawless Nb_3Sn round strand to become part of a Rutherford cable first, and of a coil next, the same cabling process affects strands of different kinds in different ways, from filament shearing to subelement merging to composite decoupling. When subject to plastic deformation, RRP subelements were found to merge into each other, creating larger filaments with a somewhat continuous barrier. If filaments are fused together, the strand sees a larger d_{eff} and its instability can dramatically increase locally. In an attempt to reduce this effect, in FY06 OST developed for FNAL a modified RRP strand design with larger Cu spacing between subelements arranged in a 60/61 array. Strand samples of various sizes of this design are first evaluated for transport properties. A comparison study then follows between the regular 54/61 strand and the modified 60/61 design using 0.7 mm round and deformed strands.

1. INTRODUCTION

Using microscopic analysis, it was found that the modified 60/61 design produced by OST with increased thickness between subelements is effective in reducing merging, where the mechanism into play is that of providing a barrier to merging not as much during the deformation process as during reaction [1]. This note covers instead transport properties of this strand.

When first evaluating the modified 60/61 design using strands of various sizes, they were all given the same relative deformation, i.e. ~30%. Rolling was chosen as it produces a homogenous deformation along the length of the strand, and presumably also a reproducible number of defects under strain.

The subsequent comparison study between the regular 54/61 design and the spaced 60/61 design was performed on 0.7 mm strands, which were rolled down to a number of thickness values to cover a large range of deformations. This study compares the effect of increasing deformation on I_c, I_S and RRR between the two designs.

Unless otherwise specified, all the results included here were obtained at 4.2 K.

2. STRAND DESCRIPTION

Table I shows properties of the 60/61 subelement strand with increased Cu spacing (Billet ID 8853), and of a billet (ID 8817) representing the latest generation of the original 54/61 subelement design [2]. The two values for the subelement size represent the average shortest and longest sizes of all subelements in a cross section. It can be seen that the 60/61 design has slightly smaller subelements. Pictures of the cross sections are in Fig. 1. Data provided by OST on billet 8853 are in Tables II and III.

3. SAMPLE PREPARATION AND TEST PROCEDURE

The strand samples were wound and heat treated in Argon atmosphere on grooved cylindrical barrels made of Ti-alloy. All the strands used in this study were given the same nominal heat treatment of 25°C/h up to 210°C, 50 h; 50°C/h up to 400°C, 50 h; 75°C/h up to 640°C, 60 h. Fig. 2 shows for instance the actual heat treatment obtained in the first evaluation study as recorded by two K-type calibrated thermocouples. After reaction, the samples were tested on the same barrel. The I_c was determined from the voltage-current (V-I) curve using the 10^{-14} Ω·m resistivity criterion. The stability current, I_S, is obtained through V-H tests as the minimum quench current in the presence of a magnetic field variation.

To test I_c and I_S, two orientations were used for the rolled strand with respect to the external magnetic field, as shown in Fig. 3. These are the so-called short edge configuration, at left, where the longest size of the strand is perpendicular to the field, and the long edge configuration, at right, where it is the shortest size of the strand that is perpendicular to the field. In the former case, which is less mechanically stable, STYCAST was used for the sample, whereas in the latter case no bonding agent was used.

4. RESULTS OF FIRST EVALUATION STUDY

This study was performed on strand samples of three different sizes, 1 mm, 0.8 mm and 0.7 mm, from billet 8853. These were all given the same relative deformation, i.e. ~30%, to be then compared with their round counterparts. Numeric results are shown in Table IV. The range of values in the round strand columns represent the different results obtained when testing without and with a bonding agent. Fig. 4 shows as expected a clear dependence of J_S with subelement size. Fig. 5 shows an interesting additional effect, which is that smaller subelements are less sensitive to I_c degradation.

5. I_c IN THE COMPARISON STUDY

In the following, because of the very similar Cu% of the strands under comparison, absolute as opposed to normalized properties are shown. In addition, these are given as a function of actual deformed strand size, as measured by microscopy, as opposed for instance to relative strand deformation. Figs. 6 and 7 show the I_c(12 T) comparison between the regular 54/61 design and the spaced 60/61 design in the short edge (with STYCAST) and long edge (without bonding agent) configuration respectively. Typical I_c measurement uncertainties are within ±1% at 4.2 K and 12 T. It can be seen that the 60/61 round strand has a better I_c performance. However, the I_c(12 T) degrades similarly under increasing deformation for the two strands, which is consistent with the two designs having similar subelelement sizes.

6. I_S IN THE COMPARISON STUDY

Figs. 8 and 9 show the I_S comparison between the regular 54/61 design and the spaced 60/61 design in the short edge (with STYCAST) and long edge (without bonding agent) configuration respectively. In the former case, some of the samples tested with the Teslatron 2 test station were power supply limited at 1020 A. Typical I_S reproducibilities when testing similar samples is within 20%. It can be seen that the 60/61 strand has a systematically better I_S performance over most of the deformation range, which is consistent with its reduced sensitivity to merging [1].

7. RRR IN THE COMPARISON STUDY

Figs. 10 and 11 show the RRR comparison between the regular 54/61 design and the spaced 60/61 design in the short edge (with STYCAST) and long edge (without bonding agent) configuration respectively. In this case the better capability of the 60/61 strand to withstand deformation is even more obvious. Despite a lower original RRR value in the round strand, in the rolled strands it shows consistently larger RRR values over most of the deformation range.

8. CONCLUSIONS

Using microscopic analysis, the modified 60/61 design produced by OST with increased thickness between subelements and slightly smaller subelement size was proven to be effective in reducing merging [1]. A first electrical evaluation study performed on strand samples of different sizes showed a clear dependence of J_S with subelement size as expected. When given the same 30% relative deformation, it was also found that smaller subelements are less sensitive to I_c degradation.

For a fair comparison between the regular 54/61 design and the spaced 60/61 design, a billet representing the latest generation of the original 54/61 design was chosen with very similar Cu%. Strands of 0.7 mm size were used to be rolled down to a number of thickness values to cover a large range of deformations. This study, which compared the effect of increasing deformation on I_c, I_S and RRR between the two designs, showed the following:

- The 60/61 round strand had a somewhat better I_c performance. However, the I_c(12 T) degraded similarly under increasing deformation for the two strands. This is consistent with the two designs having similar subelelement sizes.
- The 60/61 strand had a systematically better I_S performance over most of the deformation range. This is consistent with its reduced sensitivity to merging and possibly with its smaller d_{eff}.
- Despite a lower original RRR value in the round strand, in the rolled strands the 60/61 showed consistently larger RRR values over most of the deformation range. In this case the better capability of the 60/61 strand to withstand deformation is even more obvious.

Based on these results, the next R&D step at FNAL has been that of implementing the same spacing concept to billets with larger number of restacks.

REFERENCES

[1] D. Turrioni et al., “Study of Effects of Deformation in Nb_3Sn Multifilamentary Strands”, Applied Superconductivity Conference, Aug. 27-Sep. 1, 2006, Seattle, WA. Paper accepted in IEEE Trans. Appl. Sup..

[2] E. Barzi et al., “RRP Nb_3Sn Strand Studies for LARP”, Applied Superconductivity Conference, Aug. 27-Sep. 1, 2006, Seattle, WA. Paper accepted in IEEE Trans. Appl. Sup..

TABLES AND FIGURES

TABLE I
STRANDS DESCRIPTION

Billet ID	8853	8817
No. of subelements	60/61	54/61
Strand diameter, mm	0.7	0.7
Subelement size, µm	57-71	59-74
Twist pitch, mm	12	13.5
Cu, %	46	46.5

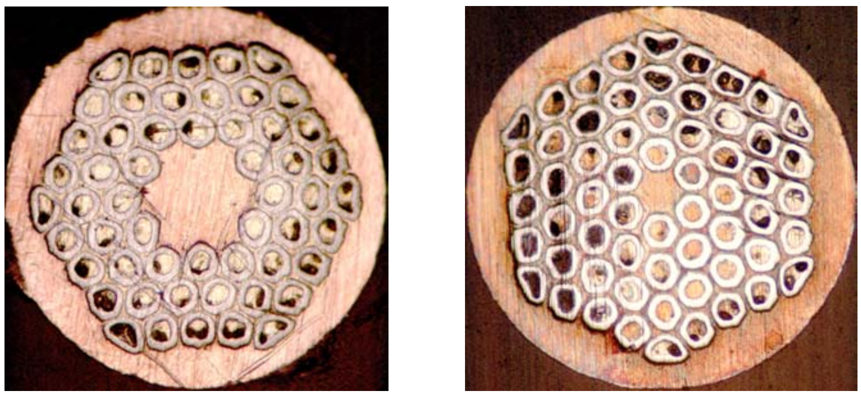

Fig. 1. Strand with 54/61 subelements (left), strand with 60/61 spaced subelements (right).

TABLE II
PIECE LENGTH DISTRIBUTION

Billet ID	Size, mm	Length, m
8853-1	0.7	1245
8853-2A	0.7	748
8853-2B1B	1.0	1994
8853-2B2B	1.0	1025

TABLE II
OST DATA

wire name	wire dia.	NC	1st stage	2nd stage	3rd stage	RRR	J_c(12T, 4K)	J_c(15T, 4K)	Kramer B_{c2} (4K)
8853-2B1A2	0.7mm	53.6%	210/48	400/48	665/50	108	3269	1765	25.3T
8853-2B1 BE	1.0mm	54.0%	210/48	400/48	695/75	120	*3075*	1750	26.8T
8853-2B2 FE	1.0mm	54.7%	210/48	400/48	695/75	109	*3075*	1728	26.4T
8853-1 FE	0.7mm	54.0%	210/48	400/48	665/50	113	3187	1709	25.1T
8853-2B1A1	0.8mm	53.8%	210/48	400/48	665/50	182	*3125*	1616	24.5T
8853-2A BE	0.7mm	54.1%	210/48	400/48	665/50	148	2975	1562	24.8T

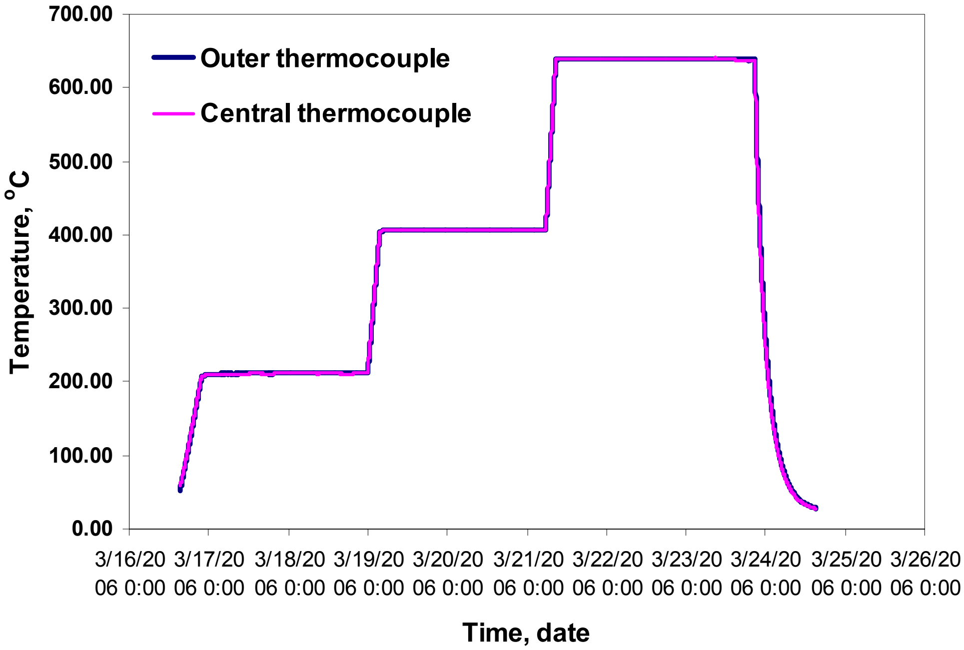

Fig. 2. Nominal strand HT was 25°C/h up to 211°C, 50 h; 50°C/h up to 407°C, 50 h; 75°C/h up to 639°C, 60 h, as average values of two calibrated K-type thermocouples.

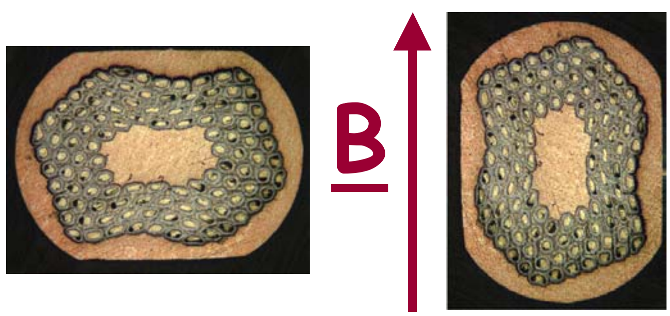

Fig. 3. Short edge configuration (left), where the longest size of the strand is perpendicular to the field, and long edge configuration (right), where it is the shortest size of the strand that is perpendicular to the field.

TABLE IV

RESULTS OF FIRST EVALUATION STUDY

Def. state	**Round**	**Rolled**	**Rolled**	**Round**	**Rolled**	**Rolled**	**Round**	**Rolled**	**Rolled**
Size	**1.0 mm**	**to 0.7 mm**	**to 0.7 mm**	**0.8 mm**	**to 0.56 mm**	**to 0.56 mm**	**0.7 mm**	**to 0.5 mm**	**to 0.5 mm**
Test config.		Long edge	Short edge (w/sty)		Long edge	Short edge (w/sty)		Long edge	Short edge (w/sty)
Cu%	46	46	46	46	46	46	46	46	46
I_c(12 T), A	1114-1159	857	925	713-732	538	639	547-571	487	518
J_c(12 T), A/mm^2	2627-2733	2021	2181	2627-2697	1982	1507	2632-2748	2343	1221
I_S, A	1350-1400	1400	1150	1200-1350	900	1050	1200-1300	750	850
J_S, A/mm^2	3183-3301	3301	2712	4421-4974	3316	2476	5744-6256	3609	2004
RRR	180-182	124	115	145-185	83	87	194-212	61	89

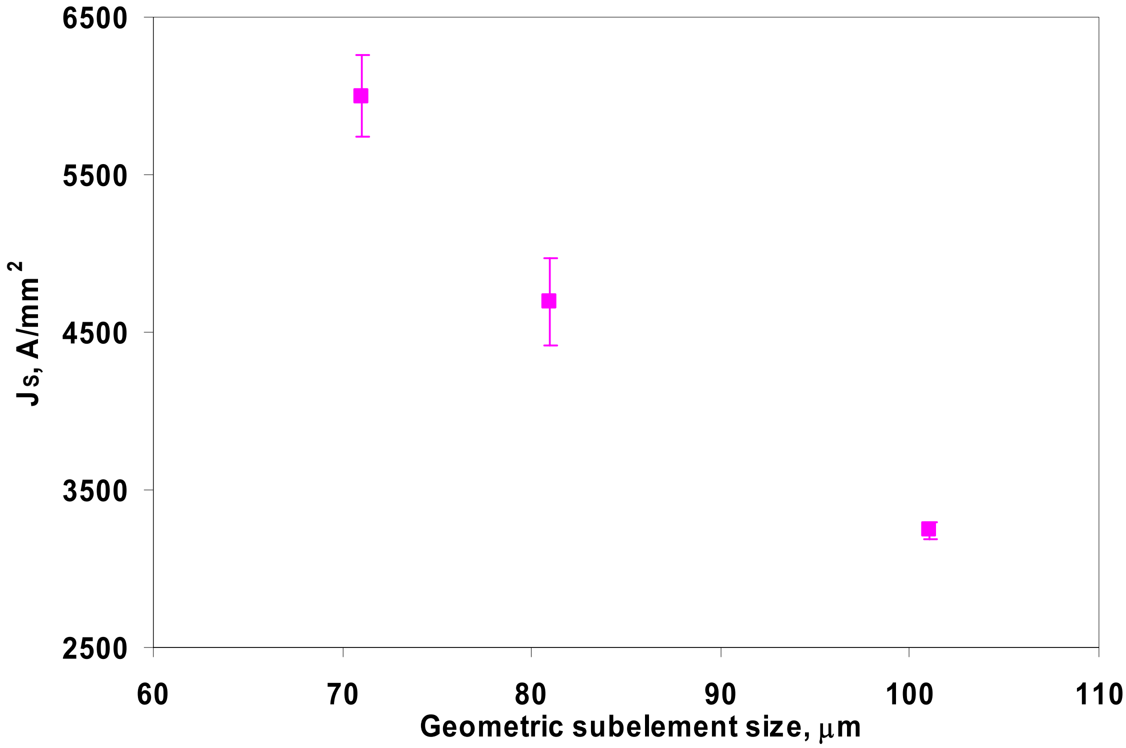

Fig. 4. J_S of the round strand from billet 8853 as a function of geometric subelement size.

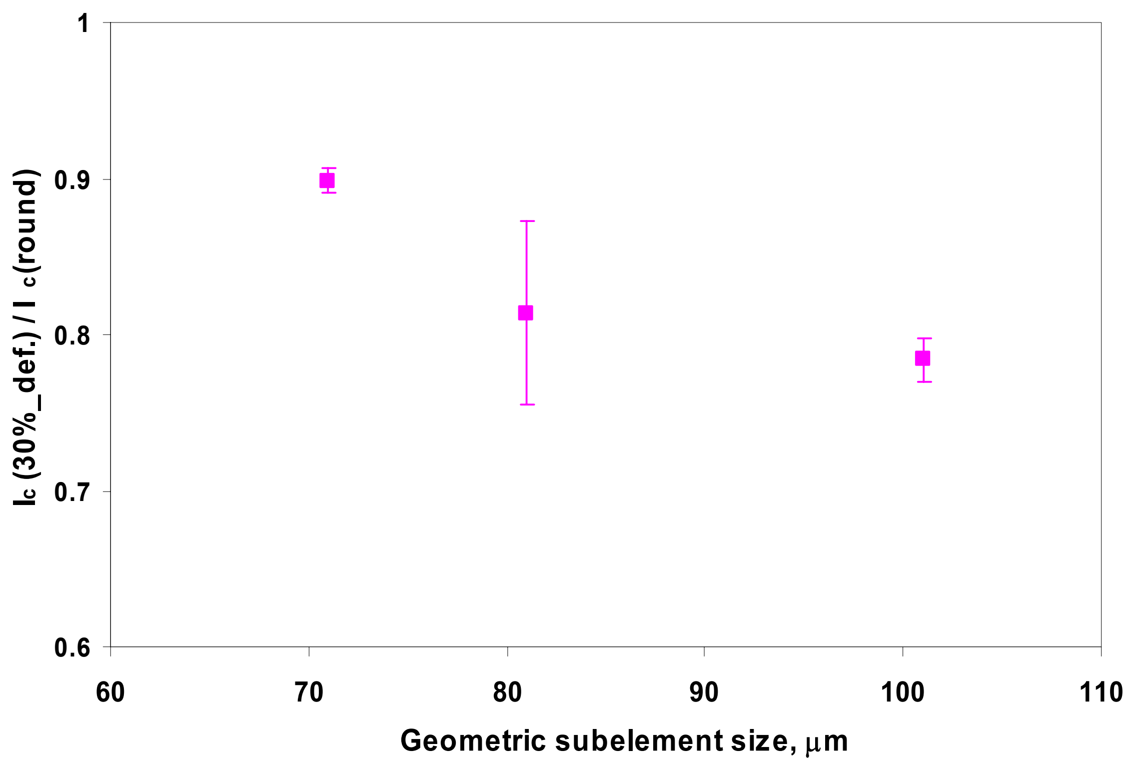

Fig. 5. I_c degradation at 12 T of strands from billet 8853 after a 30% deformation as a function of geometric subelement size of the original round strand.

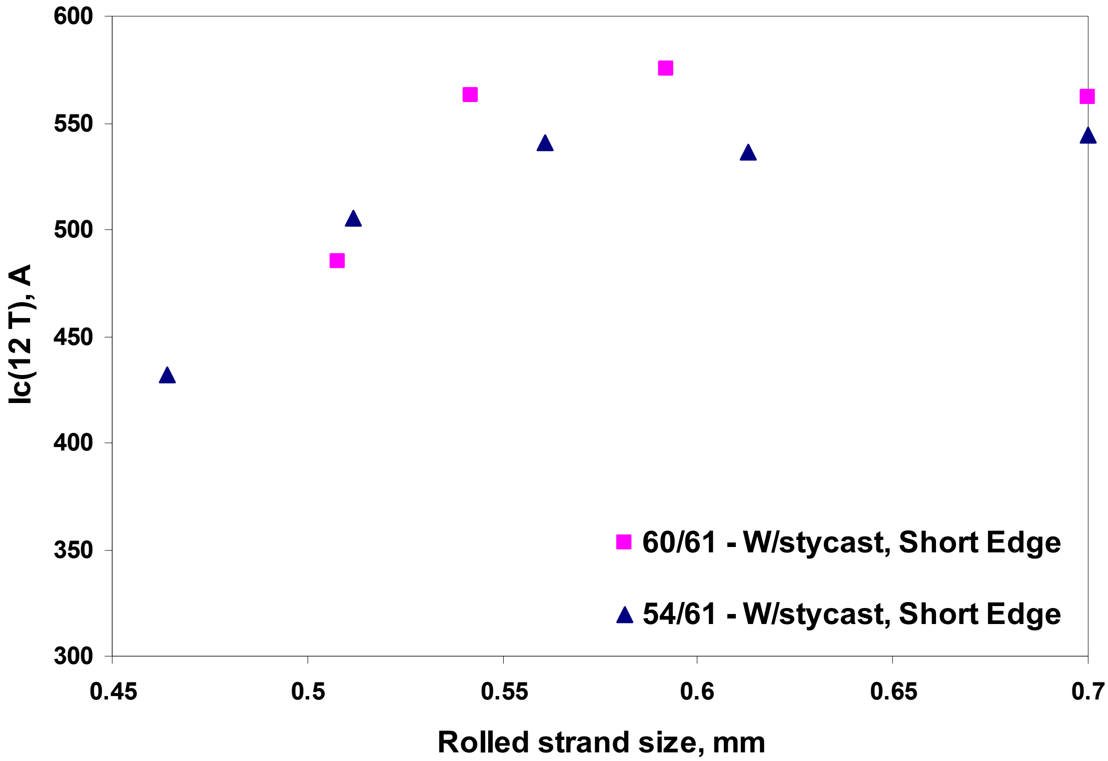

Fig. 6. I_c(12 T) of the round and rolled strands tested with STYCAST in the short edge configuration as a function of actual deformed strand size.

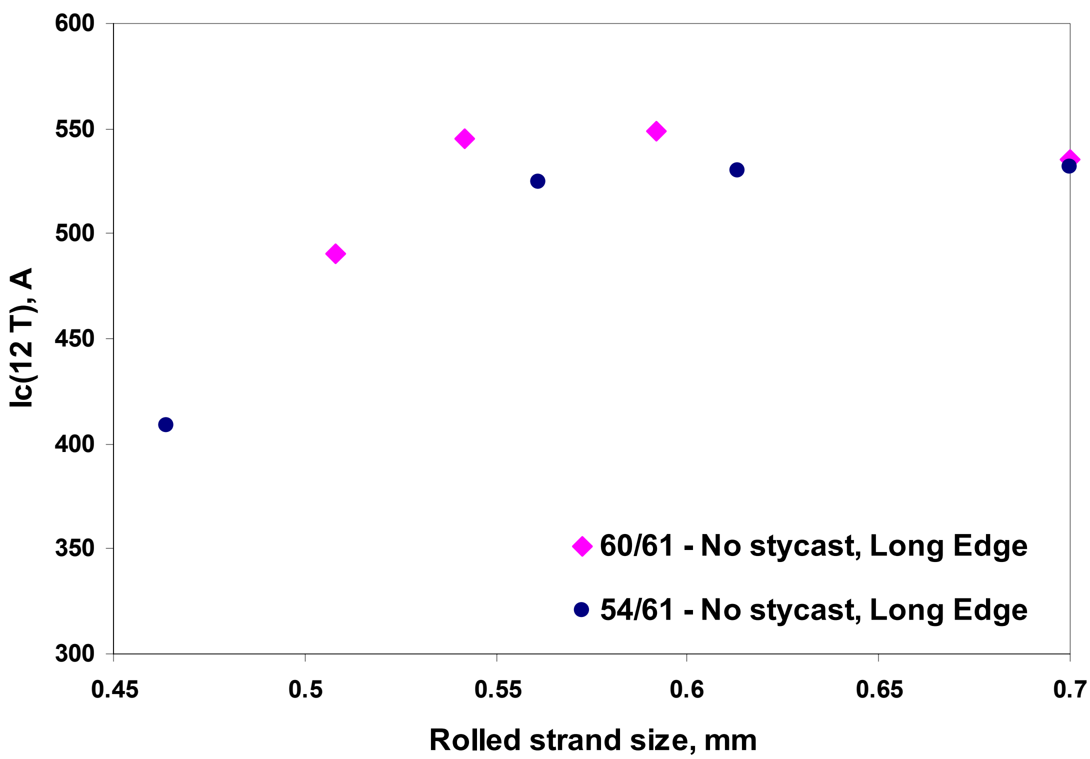

Fig. 7. I_c(12 T) of the round and rolled strands tested with no bonding agent in the long edge configuration as a function of actual deformed strand size.

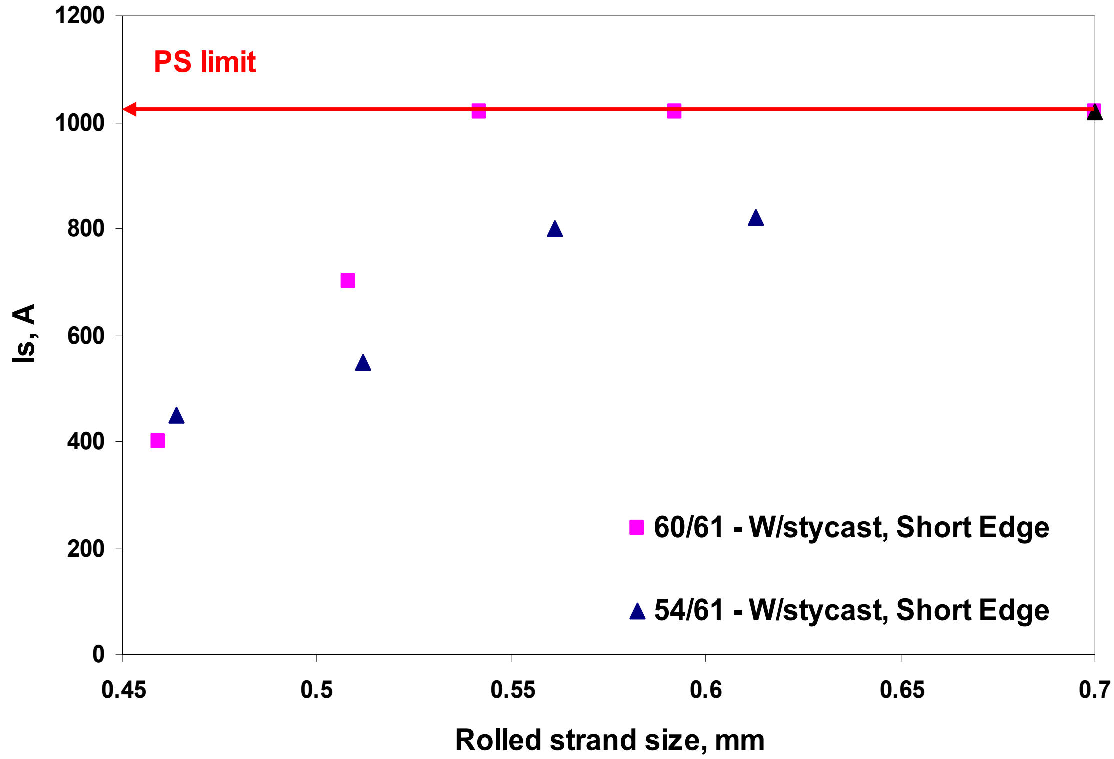

Fig. 8. I_S of the round and rolled strands tested with STYCAST in the short edge configuration as a function of actual deformed strand size.

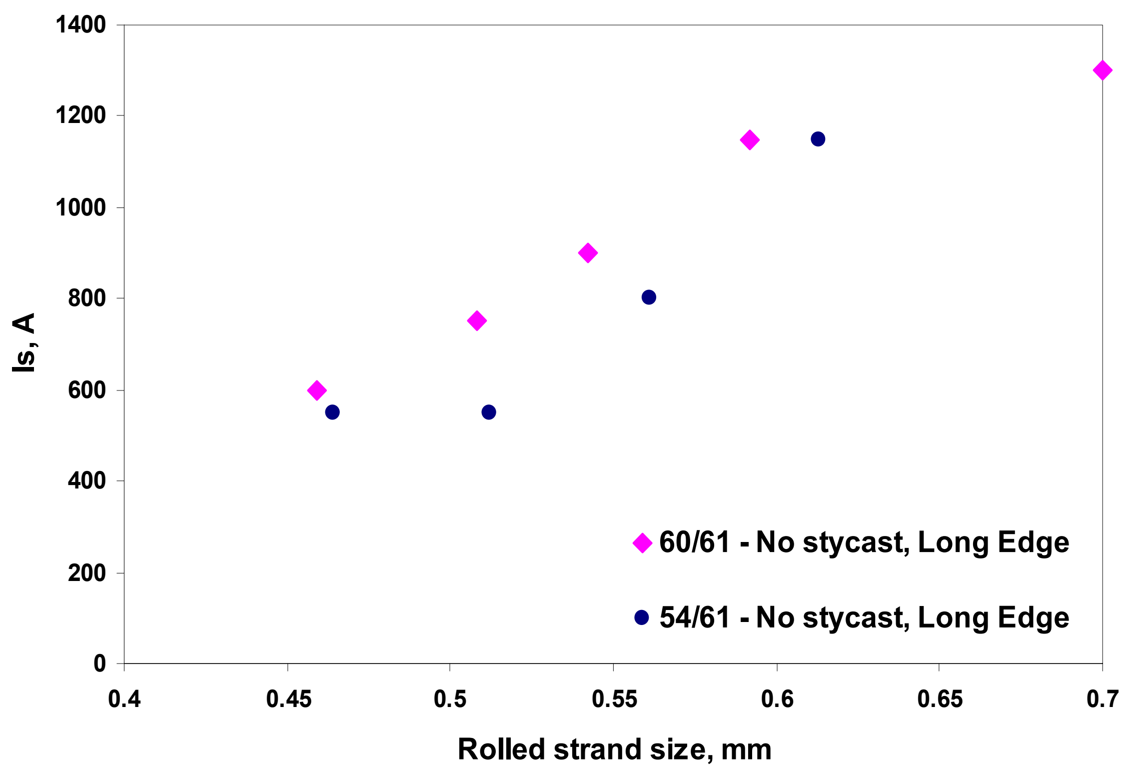

Fig. 9. I_S of the round and rolled strands tested with no bonding agent in the long edge configuration as a function of actual deformed strand size.

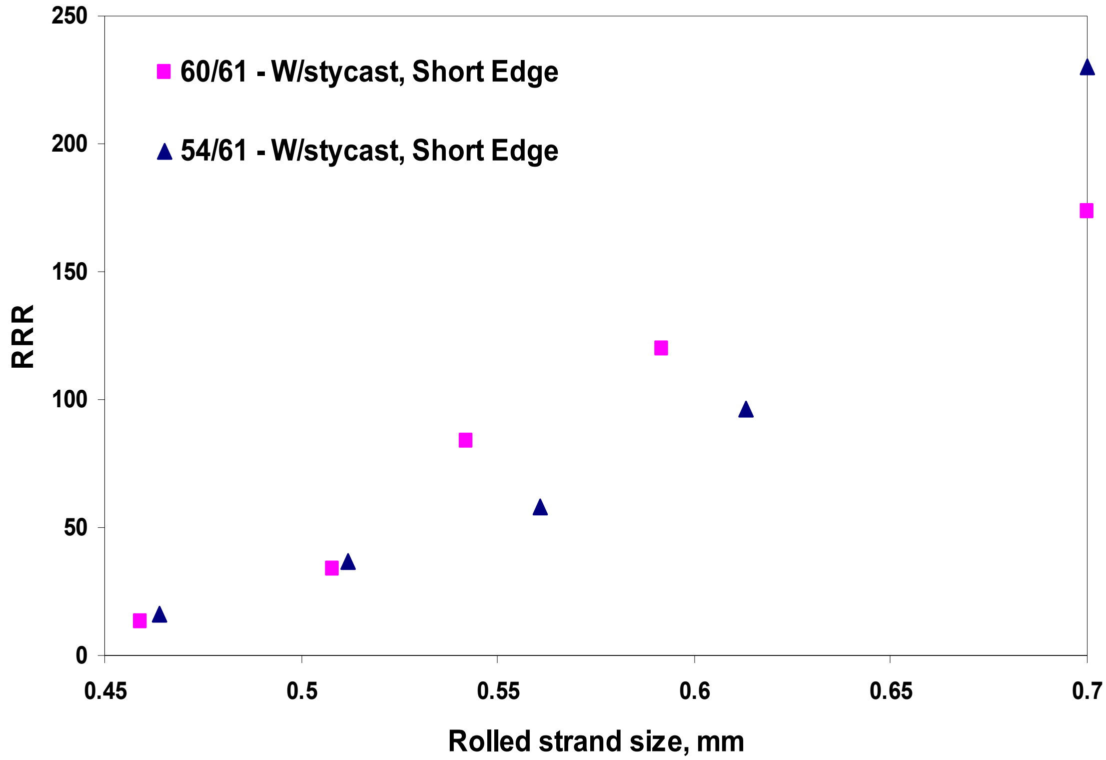

Fig. 10. RRR of the round and rolled strands with STYCAST in the short edge configuration as a function of actual deformed strand size.

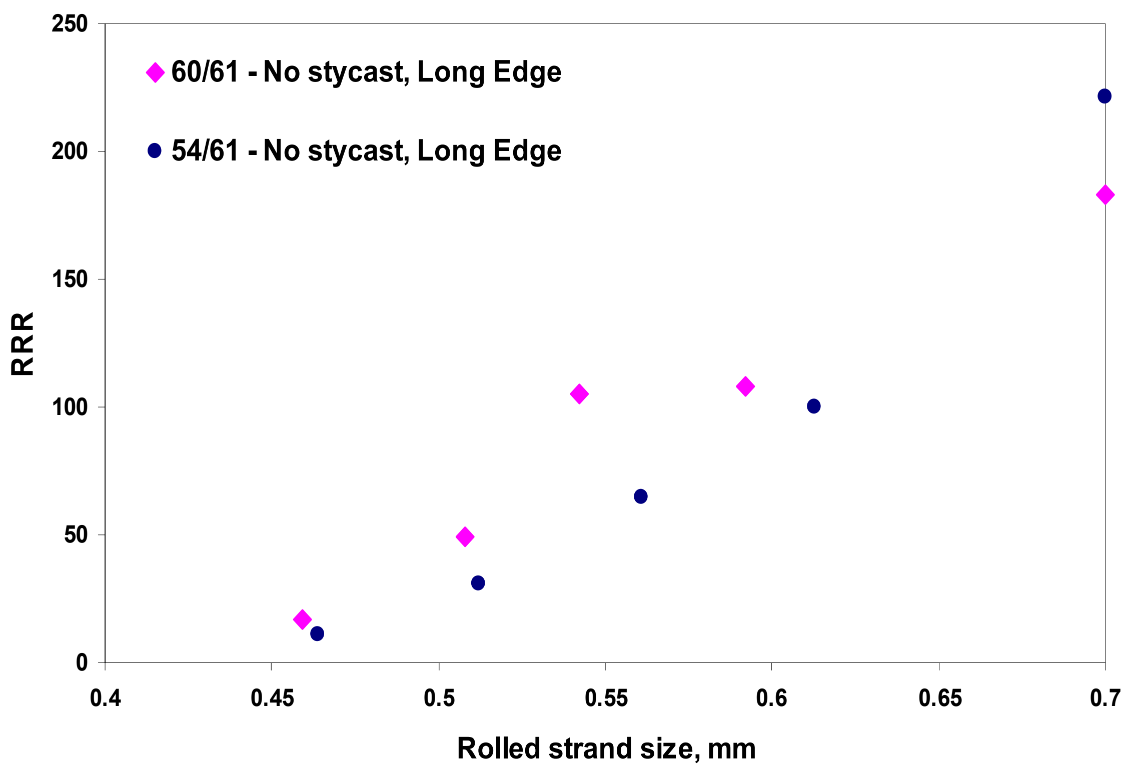

Fig. 11. RRR of the round and rolled strands tested with no bonding agent in the long edge configuration as a function of actual deformed strand size.